MINOS status and prospects

Mayly Sanchez

Argonne National Laboratory
Harvard University

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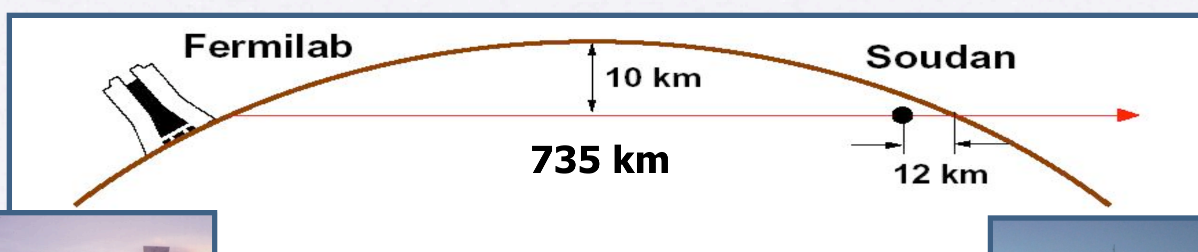
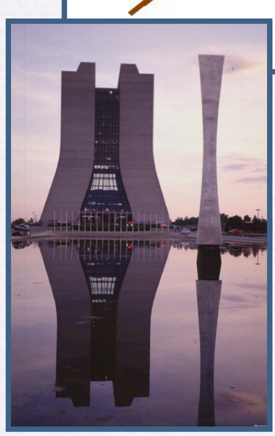
MINOS in a nutshell

- Produce a high intensity beam of neutrinos at Fermilab, measure the energy spectrum at the Near Detector. Use it to predict the Far Detector spectrum.
- If neutrinos oscillate the dip of the oscillation in the energy spectra is observed at the Far Detector in Soudan, 735 km away.





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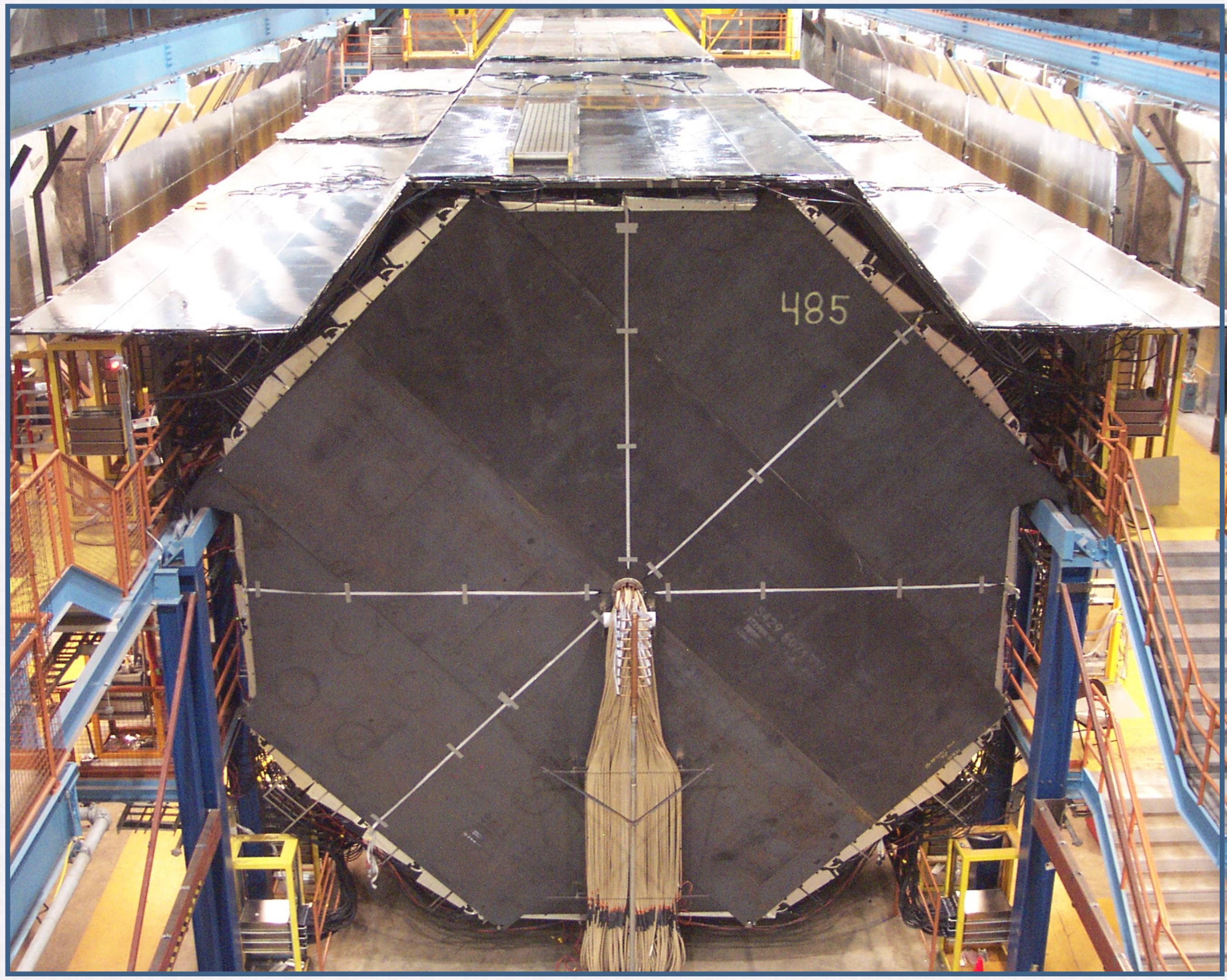
Main Injector Neutrino Oscillation Search

MINOS Physics status

- Analyses discussed in this talk:
  - ✦ Most recent ν_μ disappearance analysis
  - ✦ Test of ν_s with neutral currents
  - ✦ Search for ν_e appearance
- Other upcoming analyses:
  - Neutrino cross sections in the Near Detector
- Previously published analyses:
  - ν_μ disappearance -
    PRL (2006) and PRD (2007) published with first year data
  - Atmospheric neutrinos - PRD (2006)
  - Atmospheric muon charge ratio - PRD (2007)
  - Upward-going muons - PRD (2007)
  - Neutrinos time of flight - PRD (2007)

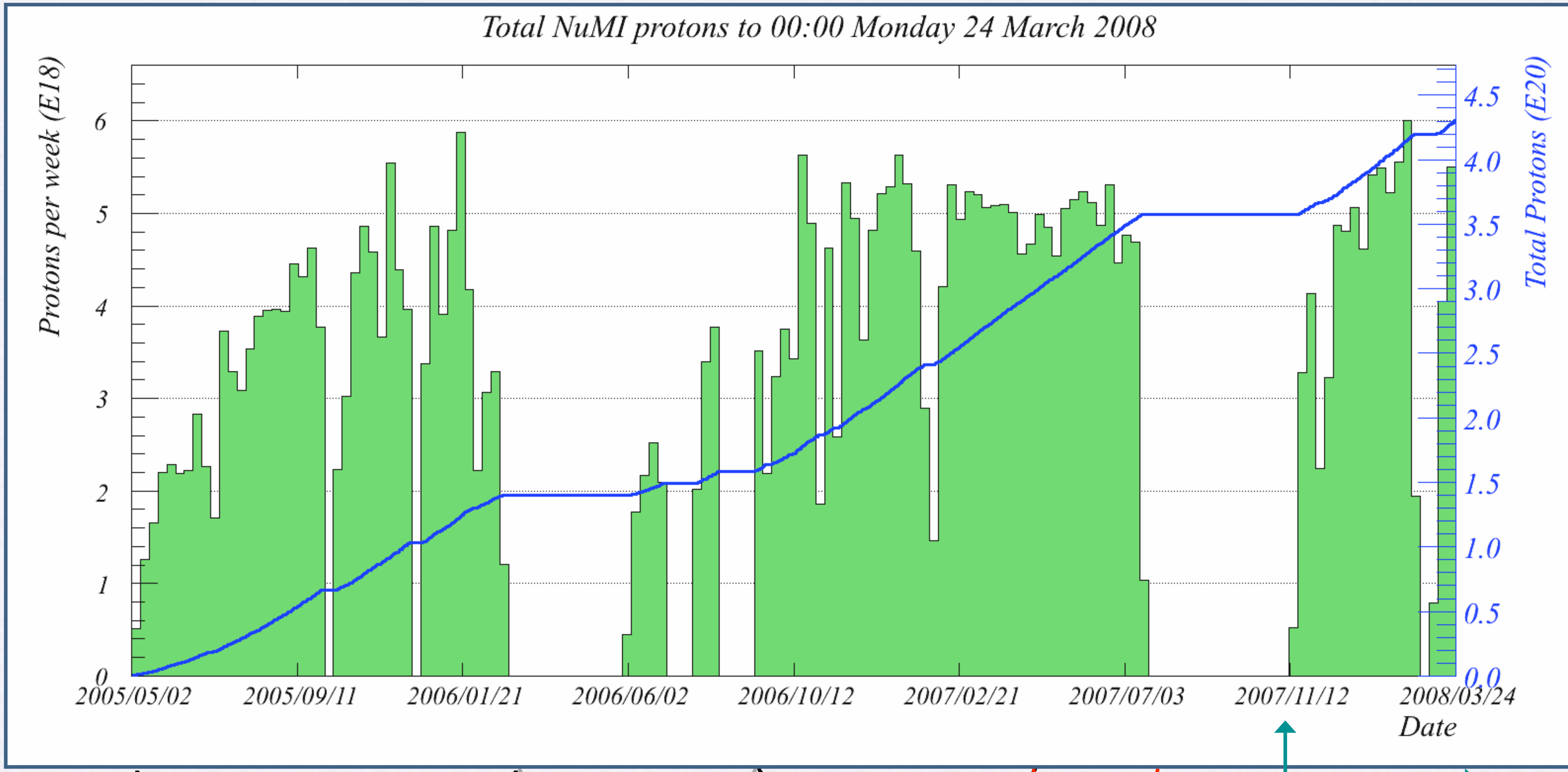
The MINOS detectors

- To first order functionally identical: Near and Far detectors
- 1 inch thick octogonal steel planes, alternating with planes of 4.1cm x 1cm scintillator strips, up to 8m long.
  - Near: ~ 1kton, 283 steel squashed octagons. Partially instrumented. 153 scintillator planes. Requires faster readout.
  - Far: 5.4 kton, 486 (8m/octagon) fully instrumented planes.



The Beam: NuMI protons

Currently analyzing data through Run II



RUN I - 1.27x10^{20} POT
(published in PRL)

Higher energy beam

RUN IIa
1.23x10^{20} POT

RUN IIb
~0.75x10^{20} POT

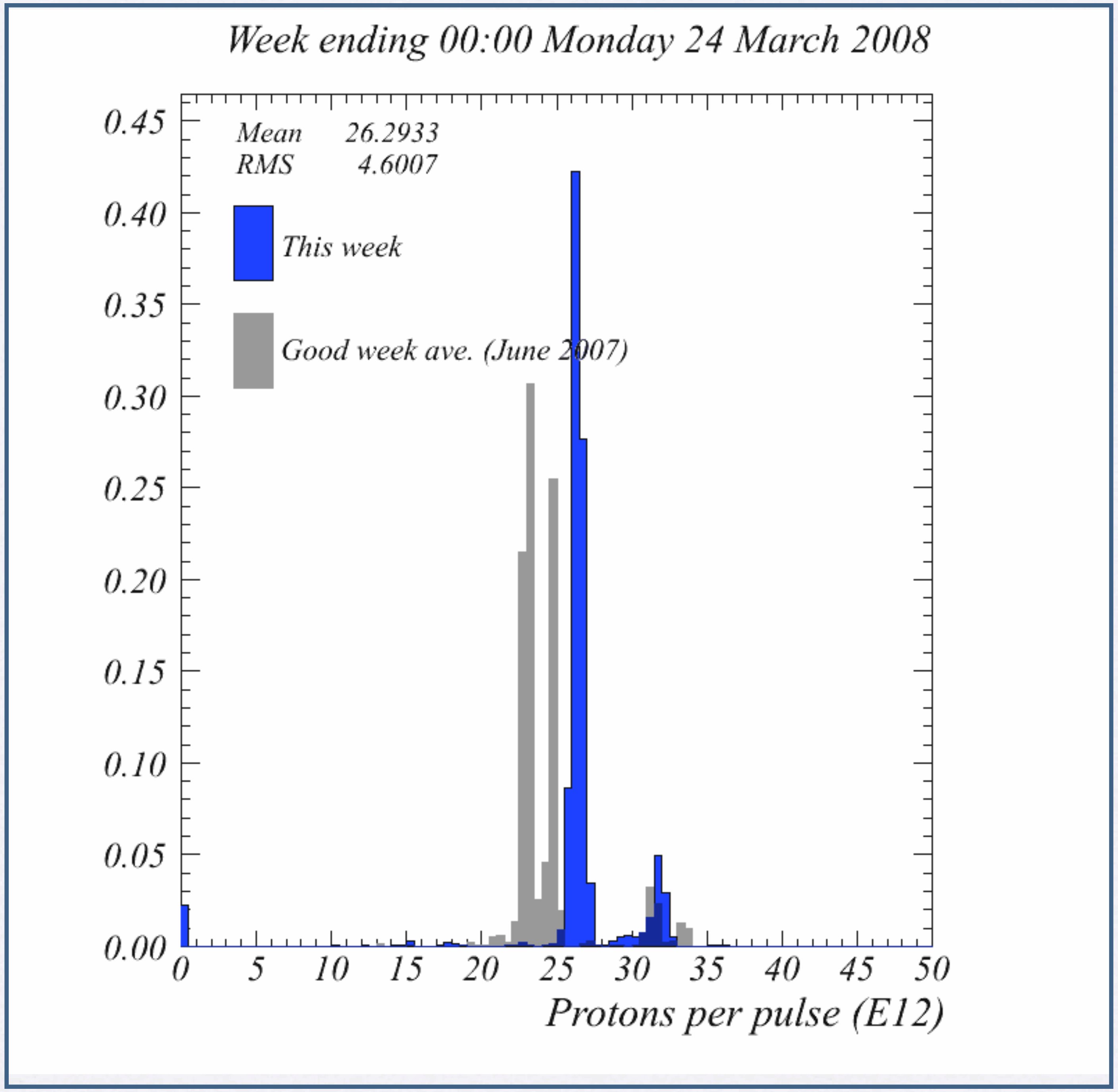
RUN III
>0.63x10^{20} POT

Results shown run I+IIa - 2.50 x 10^{20} POT

The Beam: NuMI protons

Setting new records!

- Protons per pulse:
  - ~26 x 10^{12}: 2+9 7-turns mixed
  - ~32 x 10^{12}: NuMI only (during pbar recycler transfer)
- 2.64 x 10^{13} protons per pulse compare to best week before 2.59 x 10^{13} protons per pulse
- Successful commissioning of slip-stacking



Neutrino Event Topologies

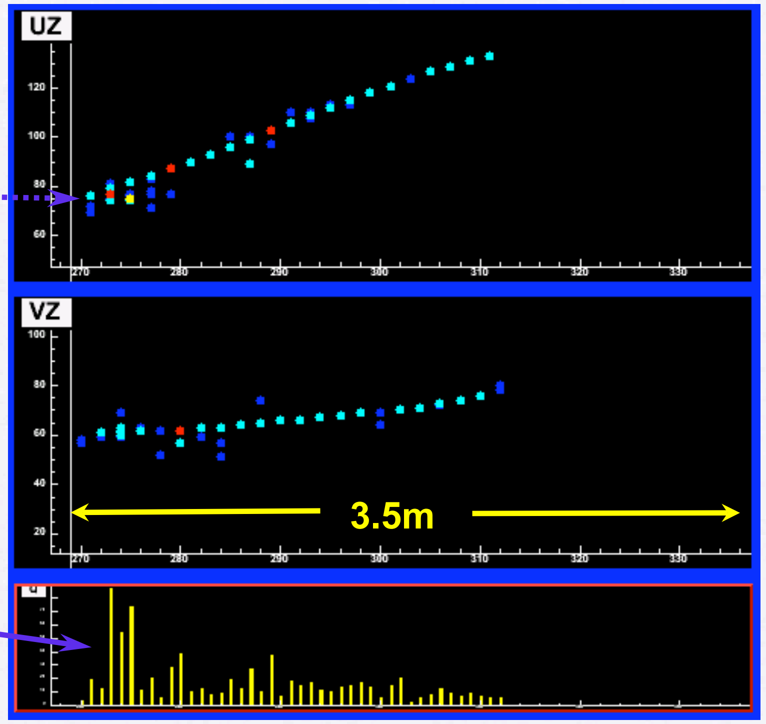
MINOS analyses use all of them!

Monte Carlo events

ν_μ CC event

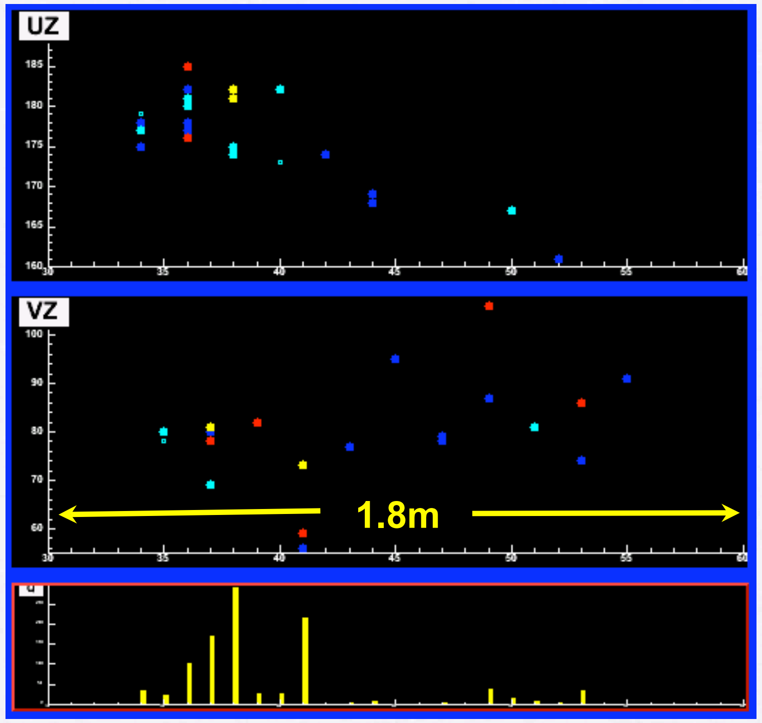
ν

- μ **track**
- **+hadronic activity**



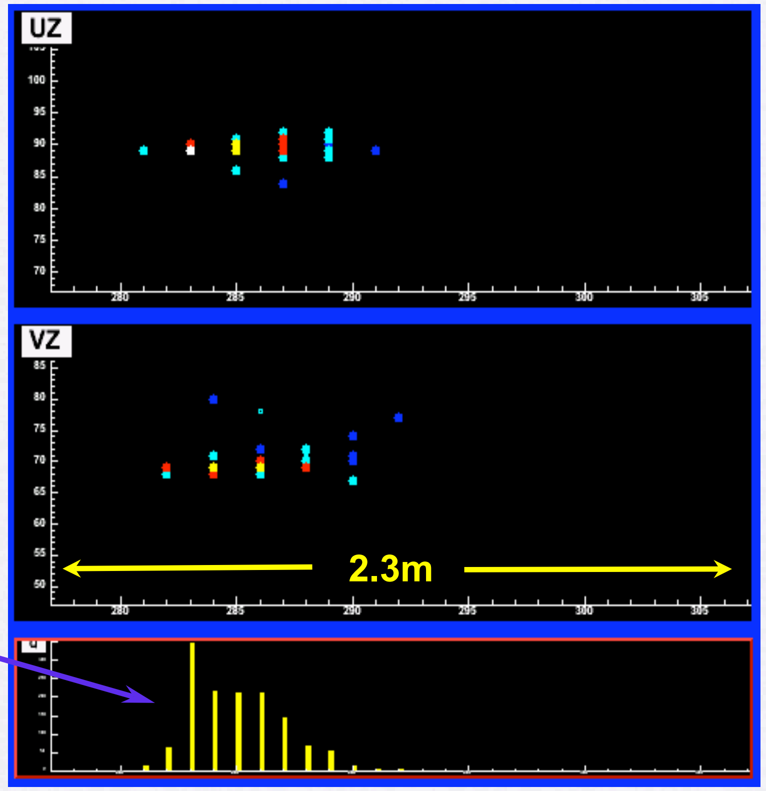
NC event

- **often diffuse**



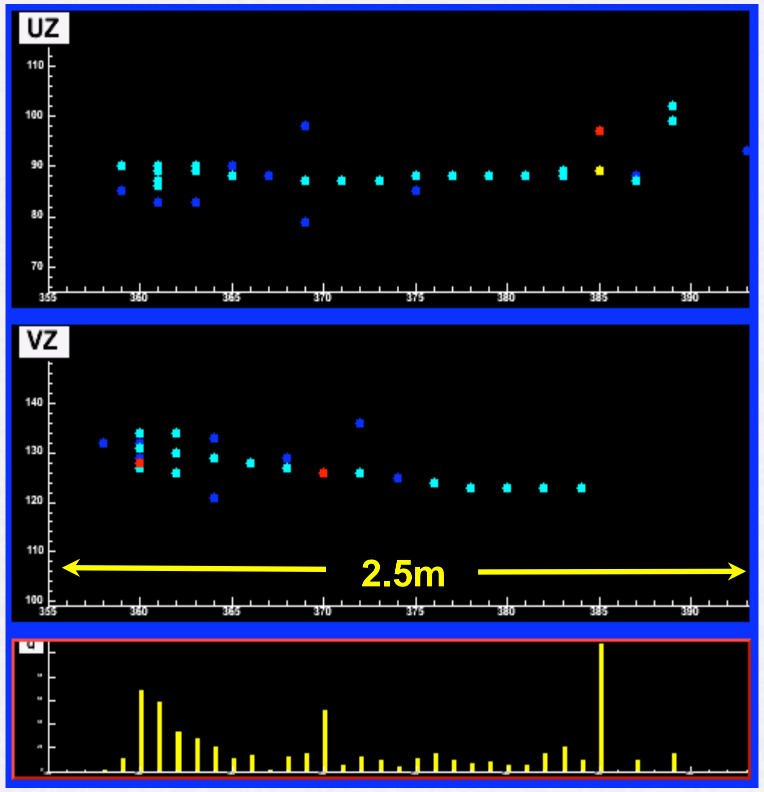
ν_e CC event

- **compact shower**
- **typical EM shower profile**



NC event

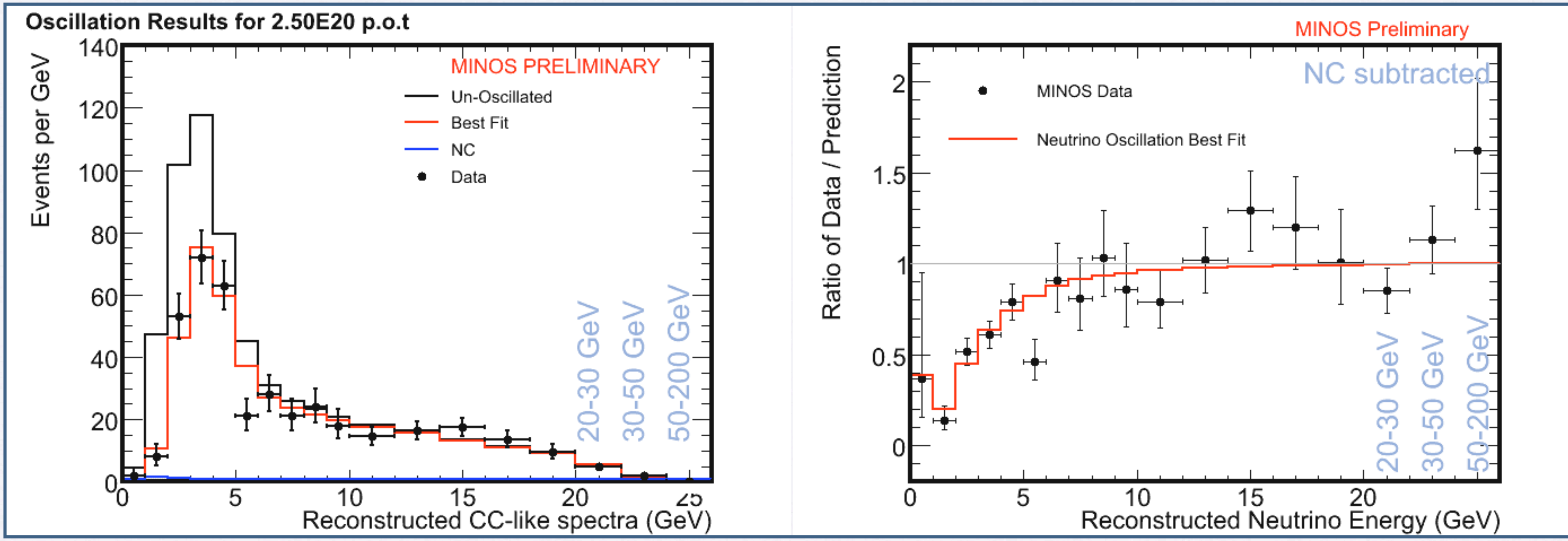
- **can mimic** ν_μ , ν_e



The ν_μ disappearance analysis:

- Run I+IIa (2.5 x 10^{20} POT) shown here
- Paper in draft form for full Run I+II (3.25 x 10^{20} POT)

ν_μ-CC energy spectrum



$|\Delta m^2_{32}| = 2.38\,^{+0.20}_{-0.16}$ (stat + syst) x 10^{-3} eV^2

$\sin^2 2\theta_{23} = 1.00\,_{-0.08}$ (stat + syst)

χ^2/ndf=41.2/34 (18 bins x 2 spectra (Run I, Run IIa) – 2) ndf

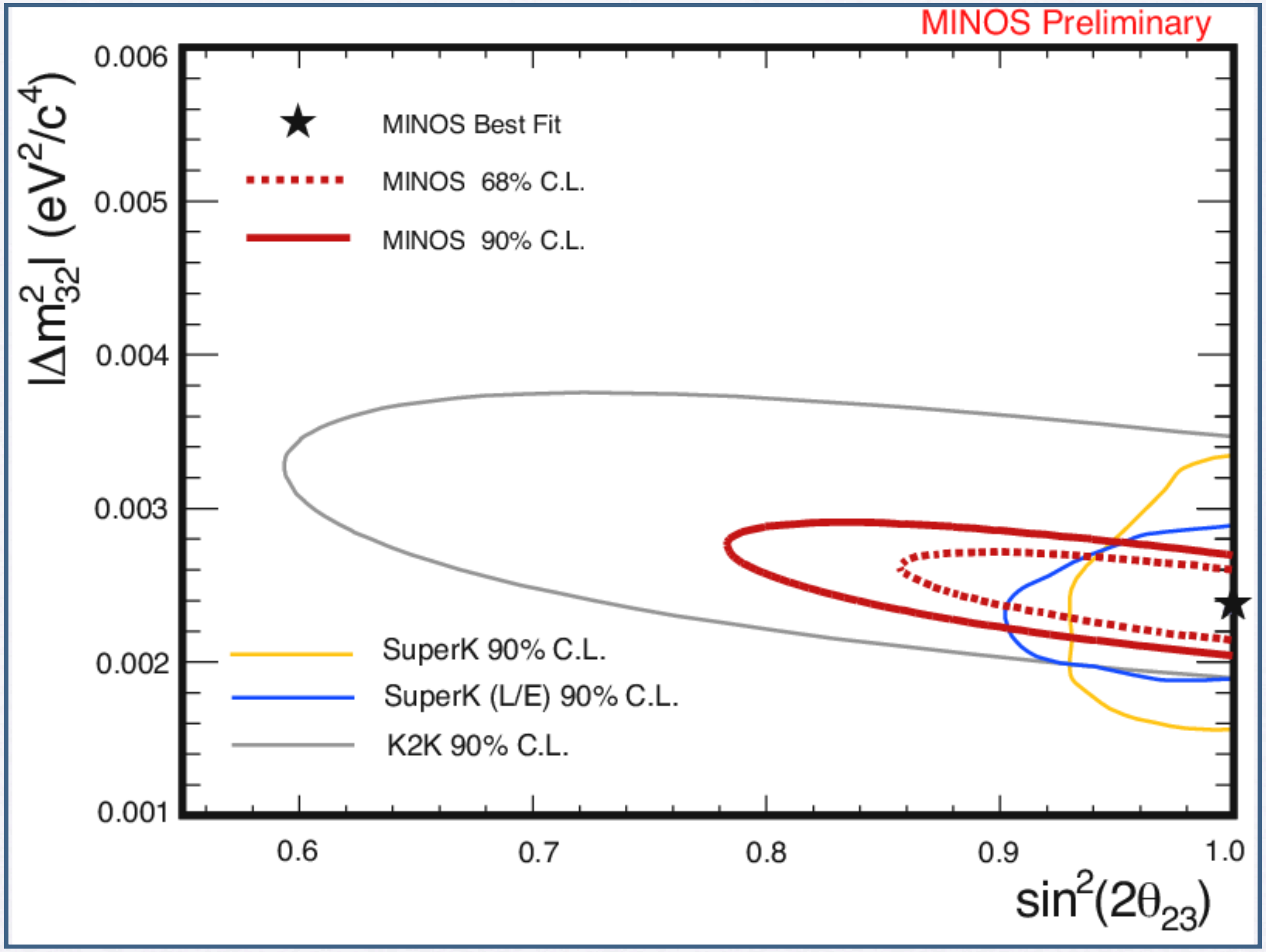
Measurement errors are 1σ, 1 DOF

$$\chi^2(\Delta m^2, \sin^2 2\theta, \alpha_j, \ldots) = \sum_{i=1}^{nbins} 2(e_i - o_i) + 2o_i \ln(o_i / e_i) + \sum_{j=1}^{nsyst} \Delta\alpha_j^2 / \sigma_{\alpha_j}^2$$

o_i = observed

e_i = expected

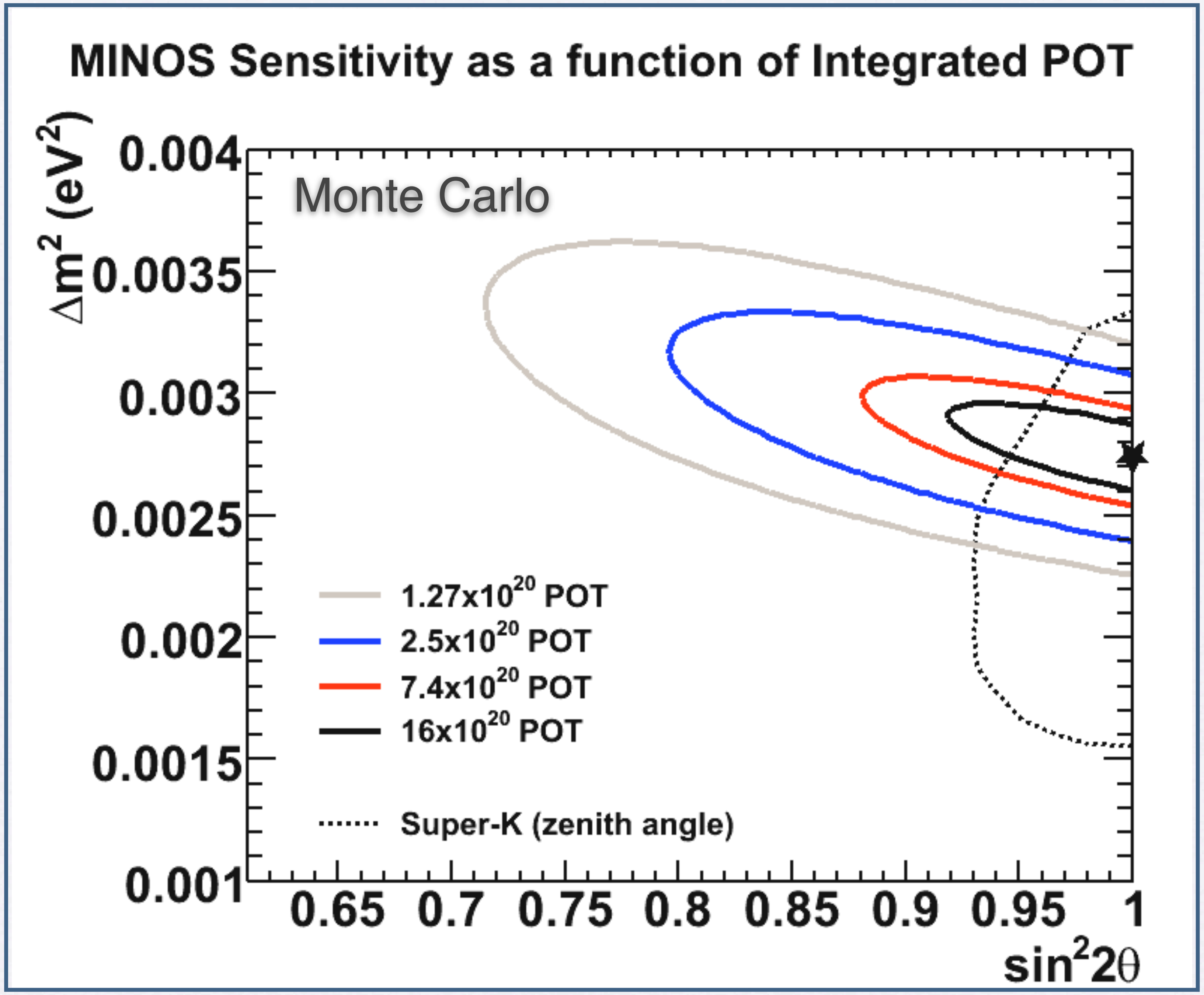
Allowed region



- Fit includes penalty terms for dominant systematics:
  - Far/Near normalization,
  - hadronic energy scale, and
  - NC contamination
- Fit is constrained to physical region: $\sin^2(2\theta_{23}) \leq 1$
- Best measurement of $|\Delta m^2_{32}|$

Results from Run I+IIa presented at Lepton-Photon 2007.

Future MINOS ν_μ sensitivity



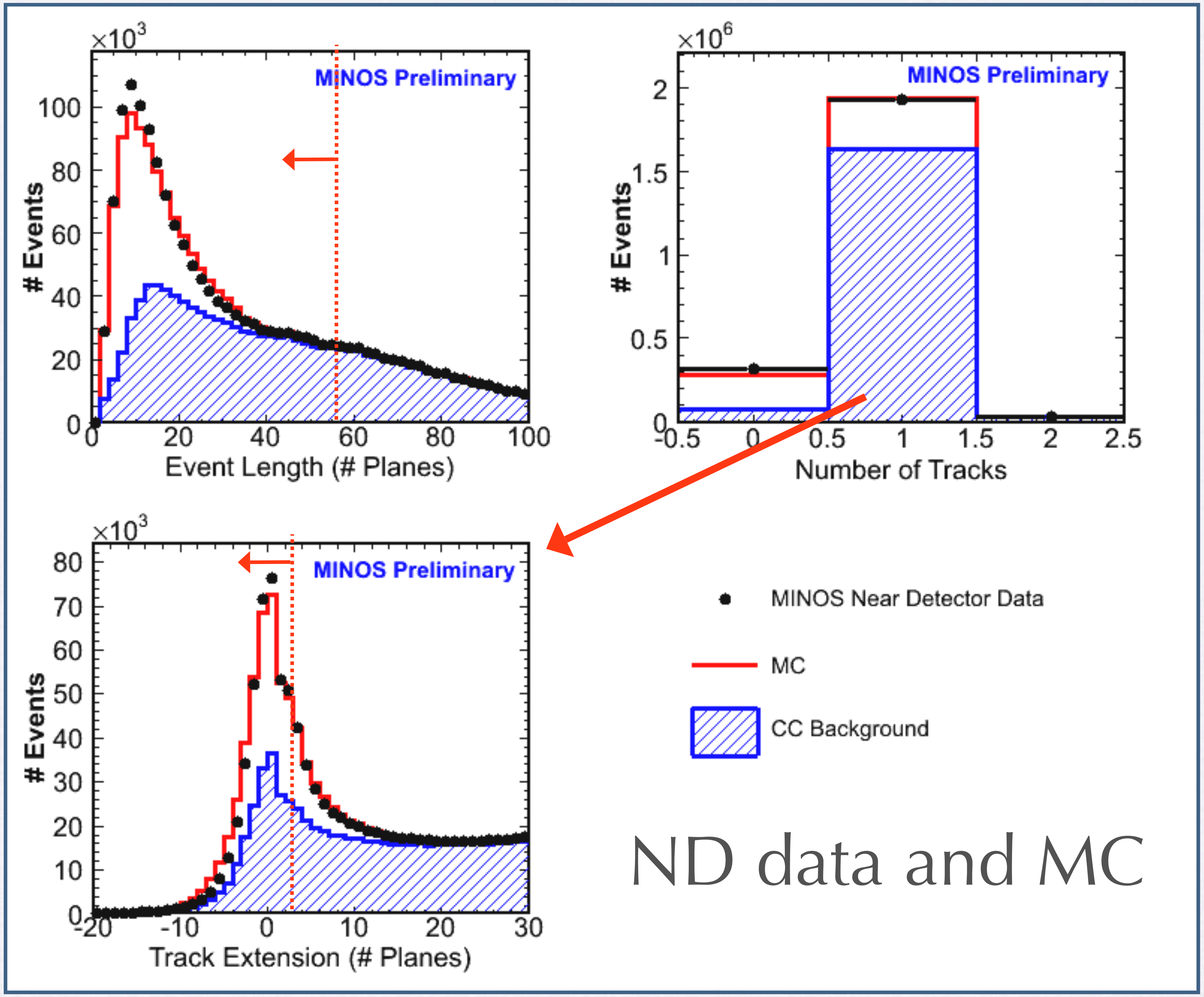
Note: based on old value of $\Delta m^2 = 2.7\times10^{-3}$ eV^2 and $\sin^2 2\theta = 1.0$
No systematics included

- Results expected shortly with 3.25×10^{20} POT:
  - More data
  - New track-based PID
  - Improved systematic errors
- Plans for future analyses:
  - Looser cuts as systematics are better understood
  - Add anti-neutrinos
  - Add rock muons
  - Search for or rule out exotic scenarios

Progress on upcoming analyses:

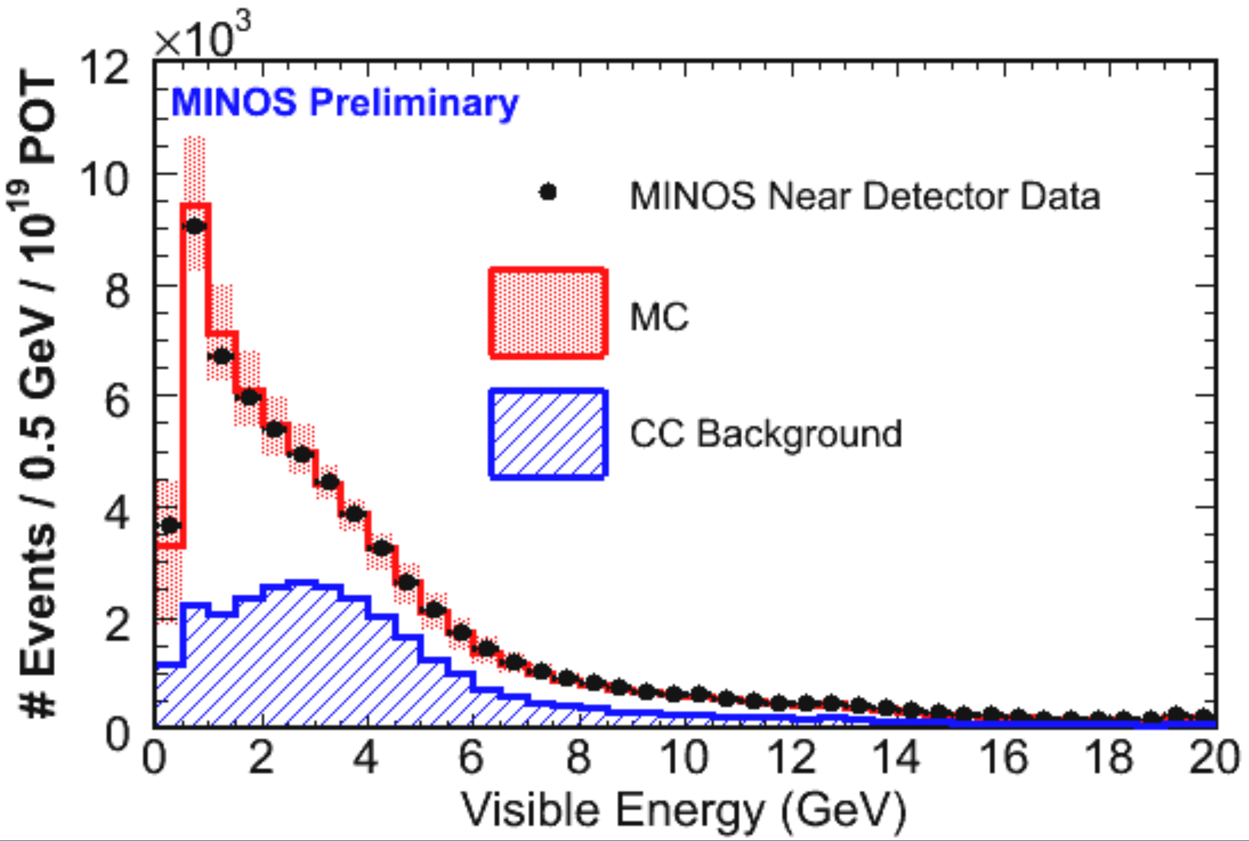
- Directly test for ν_s using NC with Run I+IIa (2.5×10^{20} POT)

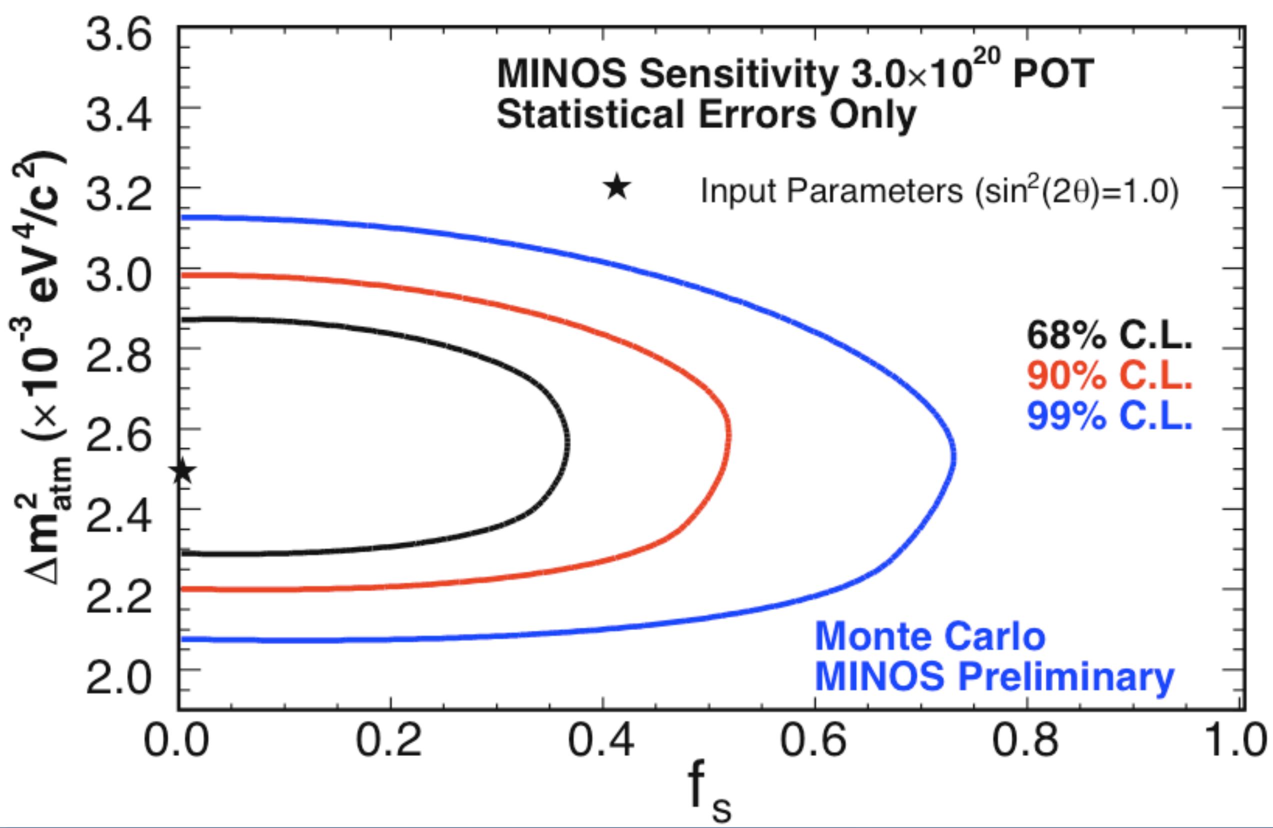
Selecting Neutral Current events



- NC events can be used to search for the sterile neutrino component
  - via disappearance of NC events in the Far Detector
- Simple NC event selection:
  - less than 60 planes;
  - no track or
  - no track extending beyond 5 planes from shower

ND data NC energy spectrum





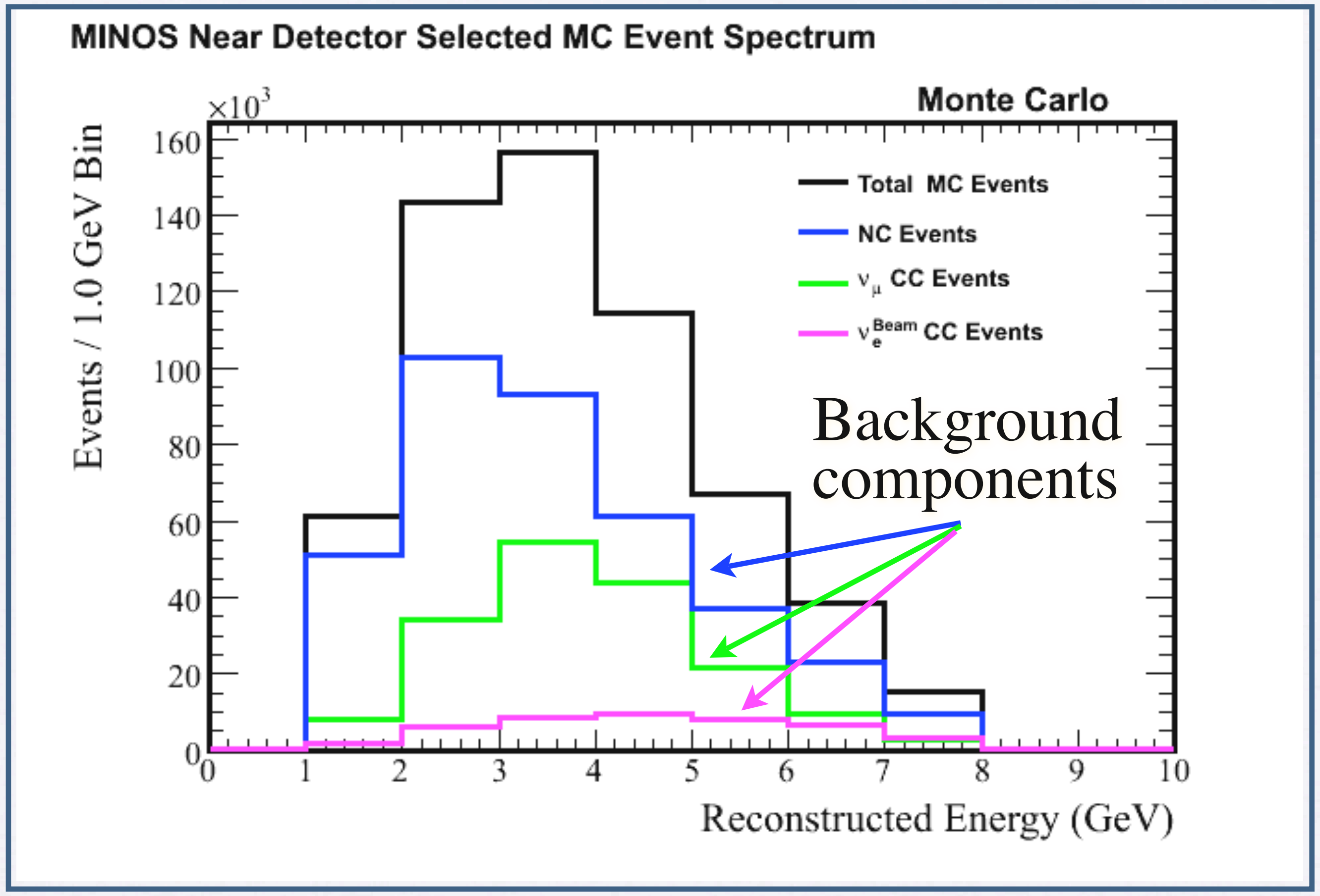
- If ν_s present, NC spectra in the Far Detector would show a deficit.
- Projected sensitivity for ν_s fraction with 3.0 x 10^{20} POT.
- Analysis with 2.5 x 10^{20} POT nearing completion, draft of paper in paper committee.

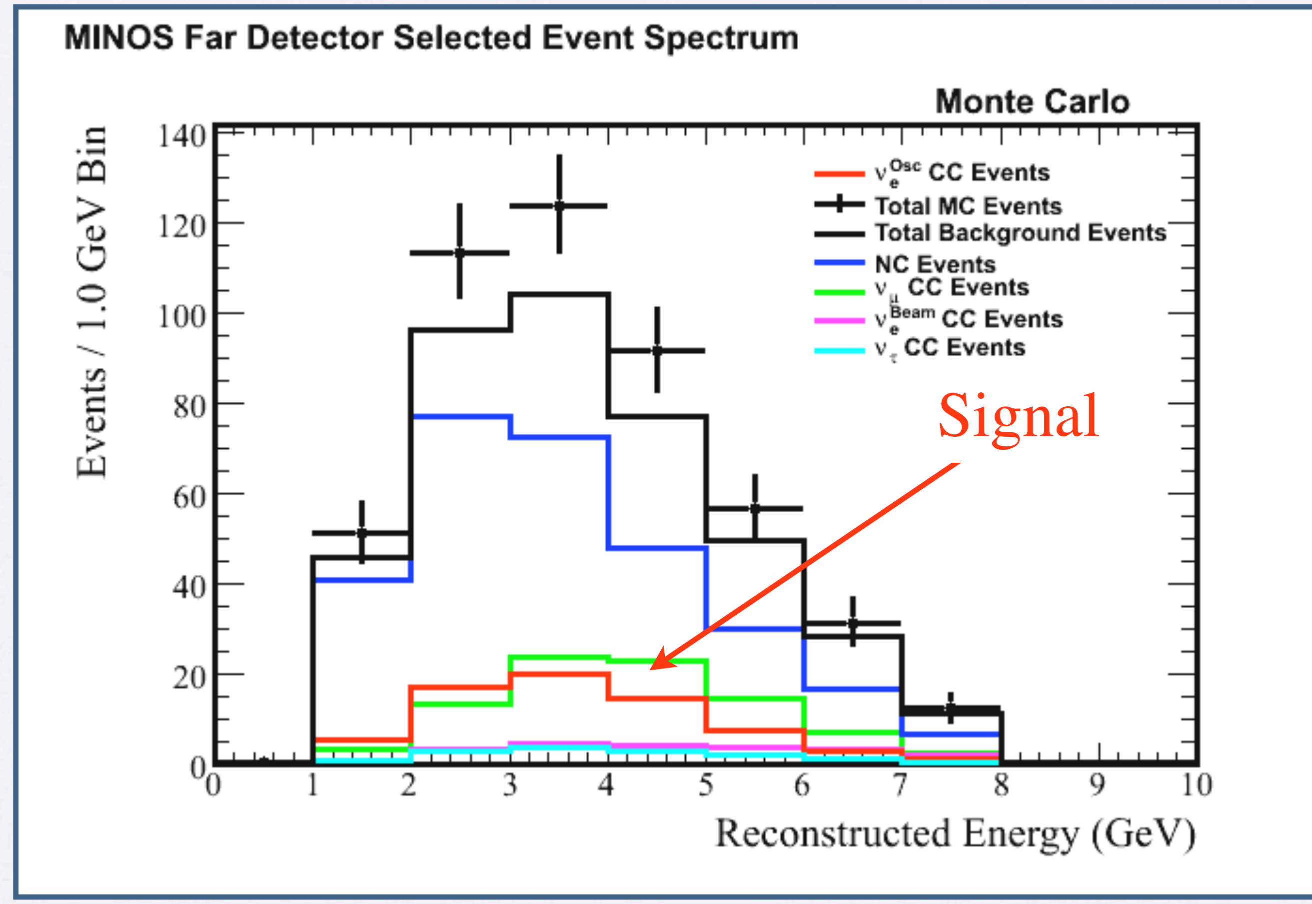
Progress on upcoming analyses:

- Search for ν_e appearance with Run I+II (3.25×10^{20} POT)

ν_e appearance in MINOS

Understanding of the background is key!

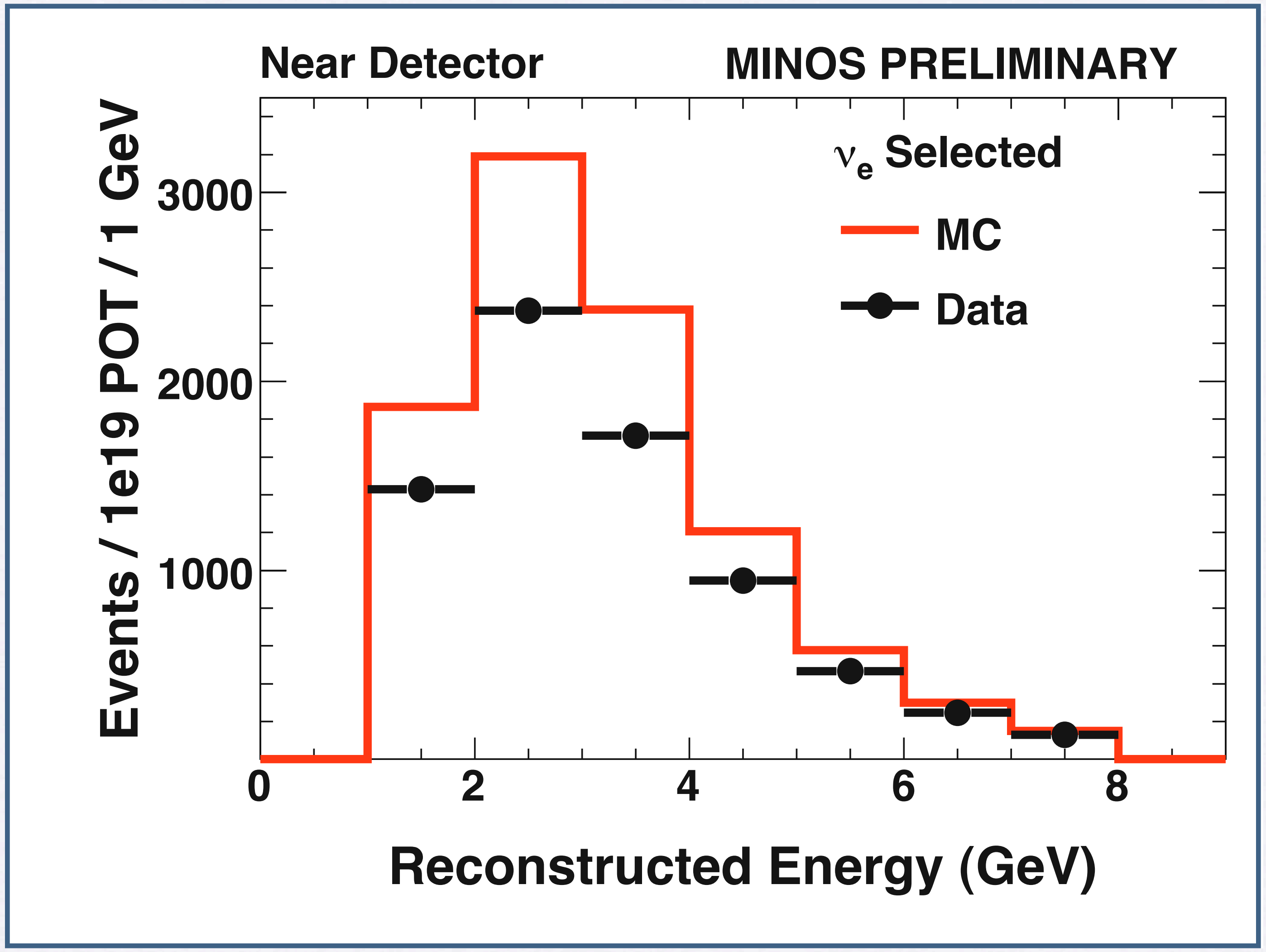




- We measure the **main background components NC, ν_μ CC and beam ν_e CC** events, in the Near Detector. We then extrapolate each of those to the Far Detector, oscillate the ν_μ CC component and obtain the ν_τ CC.
- The sum of the background components is compared to the data in the Far Detector, the difference would be the signal. The size of the signal is proportional to $\sin^2 2\theta_{13}$, expect 12 signal events for $\sin^2 2\theta_{13}=0.15$.

ν_e selected Near Detector data

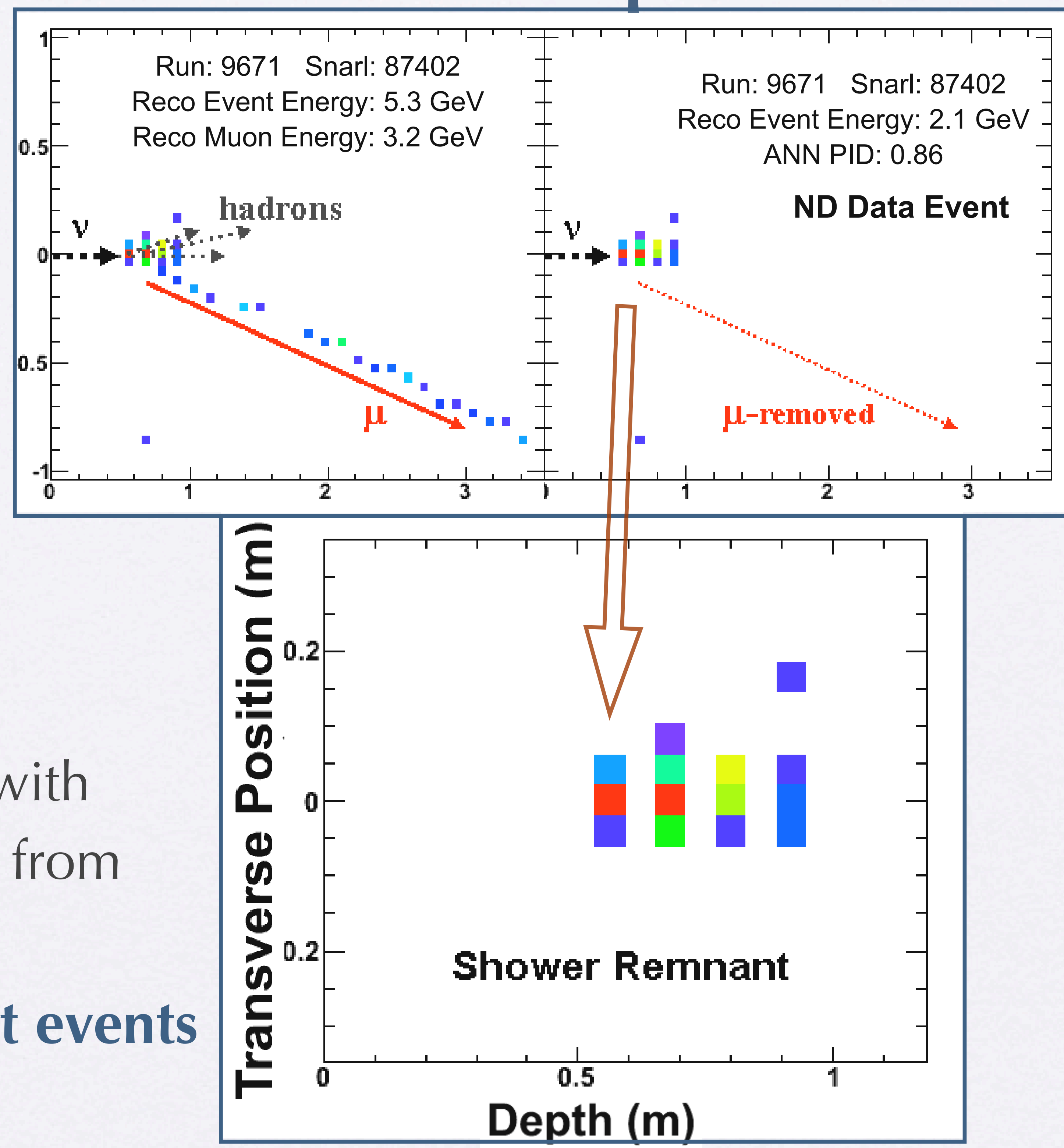
- We have developed a ν_e selection algorithm based on the electromagnetic characteristics of the showers.
- The MINOS MC has been tuned to external bubble chamber data for hadronization or fragmentation models.
- However, the literature available is for relatively higher energy than our region of interest.
- Not surprisingly, the data/MC shows disagreement with the model.



Thus, we have developed two **data-driven methods** to correct the model to match the data

Studying hadronic showers using muon removal technique

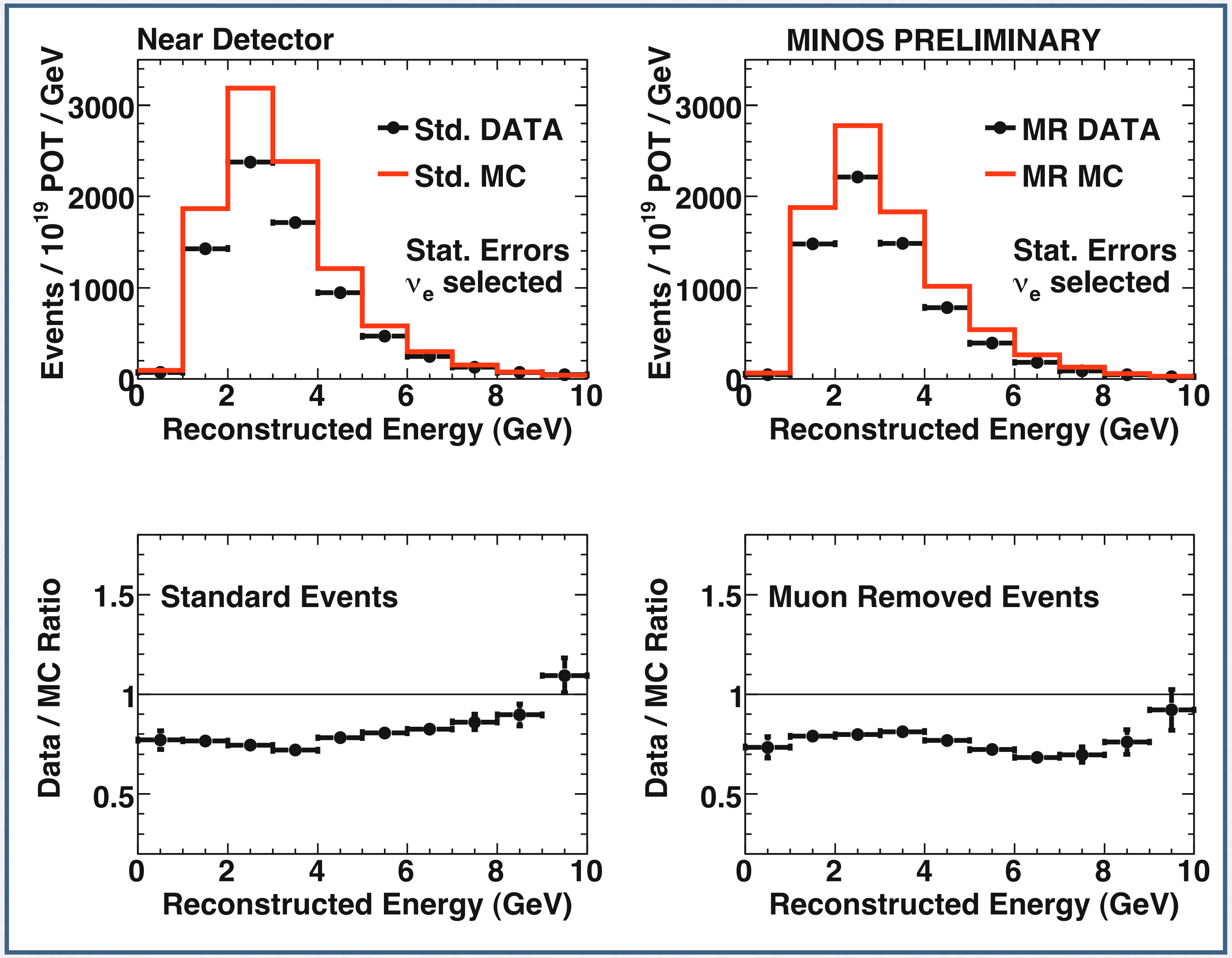
- Remove the muon track in a selected ν_μ CC event and use the rest as a hadronic shower only event.
- We use events that pass our ν_μ Charged Current event selection, i.e. that have a well defined track.
- Well understood ν_μ CC spectra, with well known efficiency and purity from the ν_μ disappearance analysis.



Muon Removed Charged Current events
⇒ MRCC events

Hadronic shower modeling in the ν_e selected data and muon-removed data

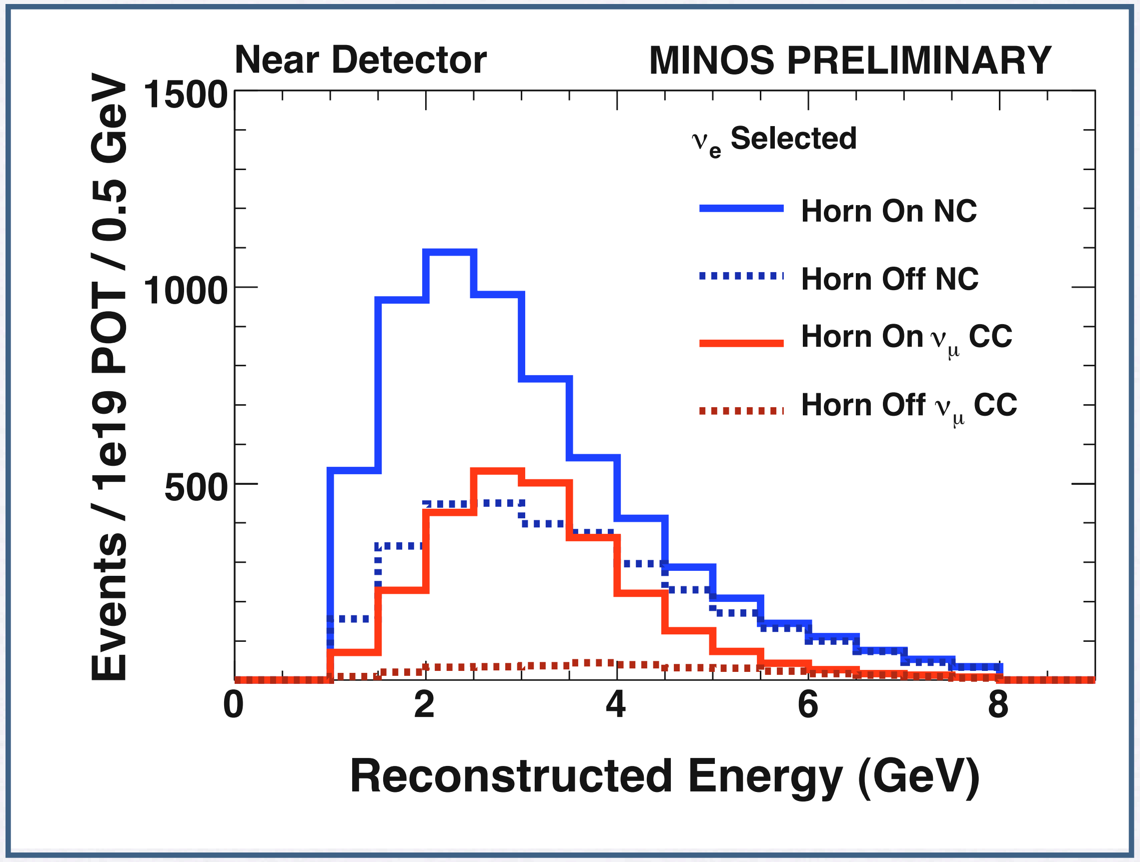
- We apply the ν_e selection to the standard data and MC as well as to the MRCC data and MC.
- Discrepancy with the model shows the same trend not only in energy but in shower topology for both sets.
- Thus modeling of the hadronic shower is a major contribution to the disagreement.
- As the MRCC sample is independent, we can use it to obtain a **data-driven correction** to the model.



Overall disagreement:
- 24.5% data/MC
- 21.5% MRCC(data/MC)

Estimating the background using horn on and horn off data

- After applying the ν_e selection cuts to the ND data, the composition of the selected events is very different with the NuMI horns on or off.



The measured flux of ν_e candidates for each case can be expressed as:

$$N^{on} = N_{NC} + N_{CC} + N_e \qquad (1)$$

$$N^{off} = r_{NC} {*} N_{NC} + r_{CC} {*} N_{CC} + r_e {*} N_e \qquad (2)$$

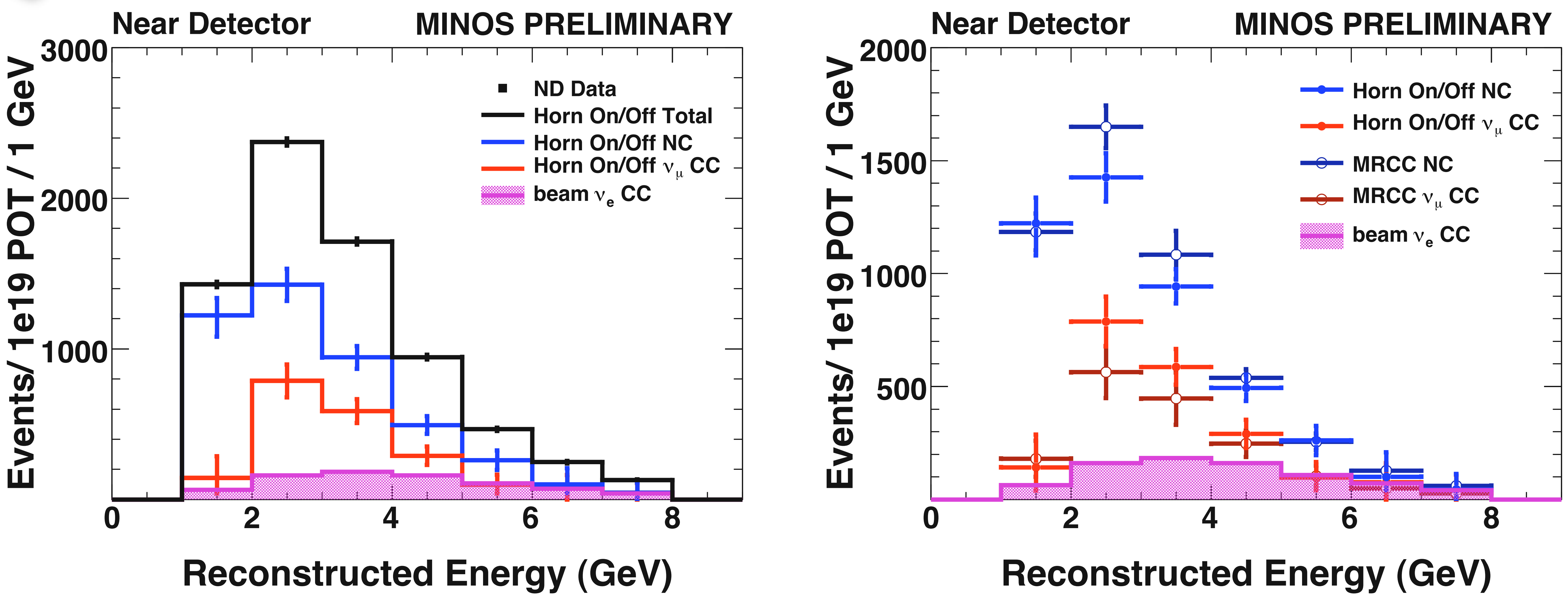
from MC:

$$r_{NC(CC,e)} = N_{NC(CC,e)}{}^{off} / N_{NC(CC,e)}$$

which can be solved to get **data-driven predictions** for NC and ν_μ CC background.

- The beam ν_e flux is obtained from the ν_μ CC flux which is constrained by data in the different beam configurations.
- Horn off/on ratios for NC and ν_μ CC events match well between data and MC.

ND data-driven background

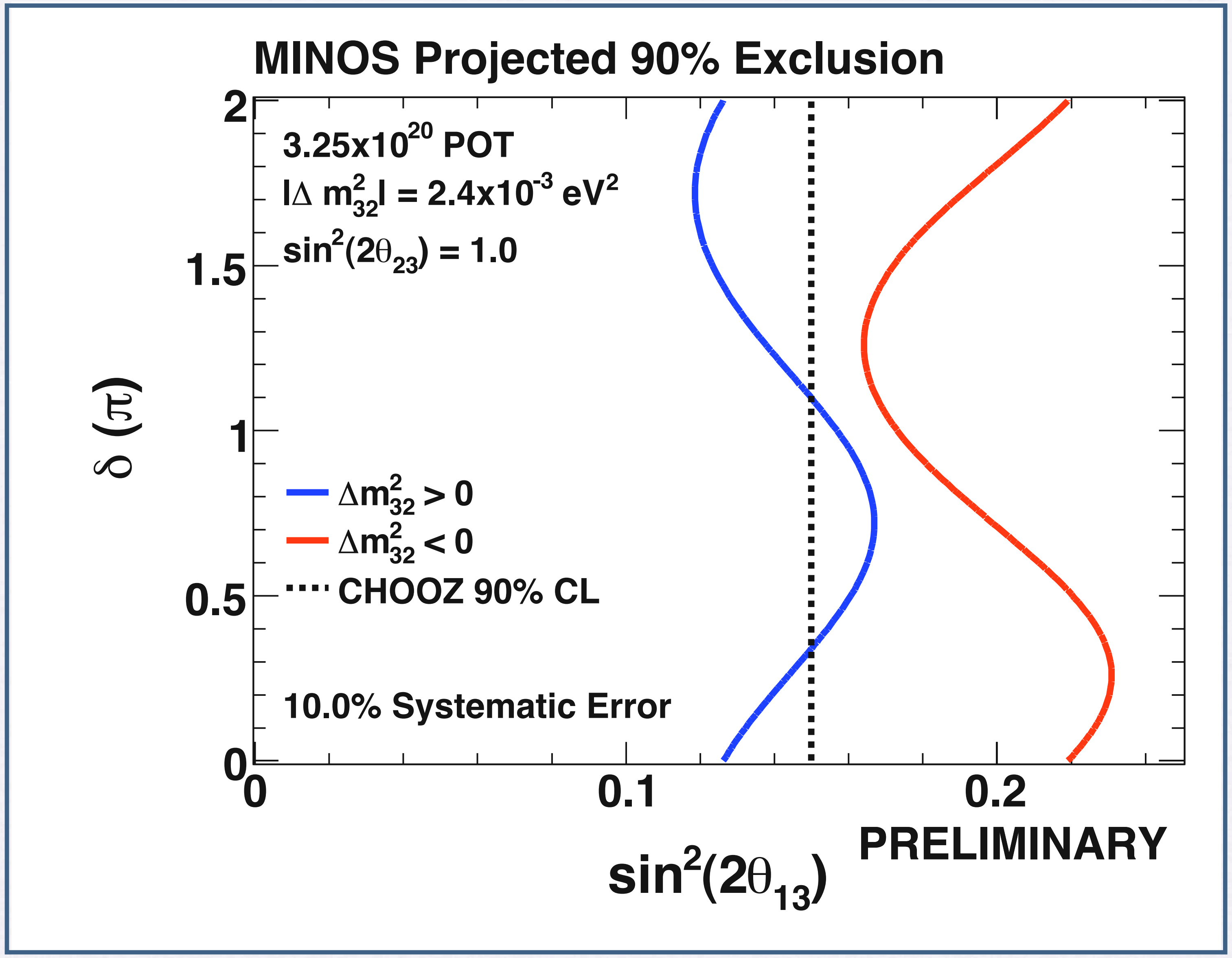


- The ν_μ CC component is obtained from subtracting the NC corrected and the beam ν_e components from the data resulting in a perfect match between the data and MC.
- The **two data-driven methods**, MRCC and Horn on/off, are in good agreement in the Near Detector NC and ν_μ CC background for the ν_e analysis.
- Each background in the Horn on/off method is then extrapolated to the Far Detector and data-driven sensitivity limits are obtained.

Physics reach of MINOS

Data-driven ν_e sensitivity

- Our preliminary expectation from the two methods is 42-43 background events in the Far Detector for run I+II.
- We have a chance at making the first measurement of θ_{13}.
  - Matter effects can significantly change ν_e yield.
- Plot shows 90% upper limit in δ_{CP} vs. $\sin^2 2\theta_{13}$ for both hierarchies at the MINOS best fit value with 3.25 x10^{20} POT
  - 10% systematic error included



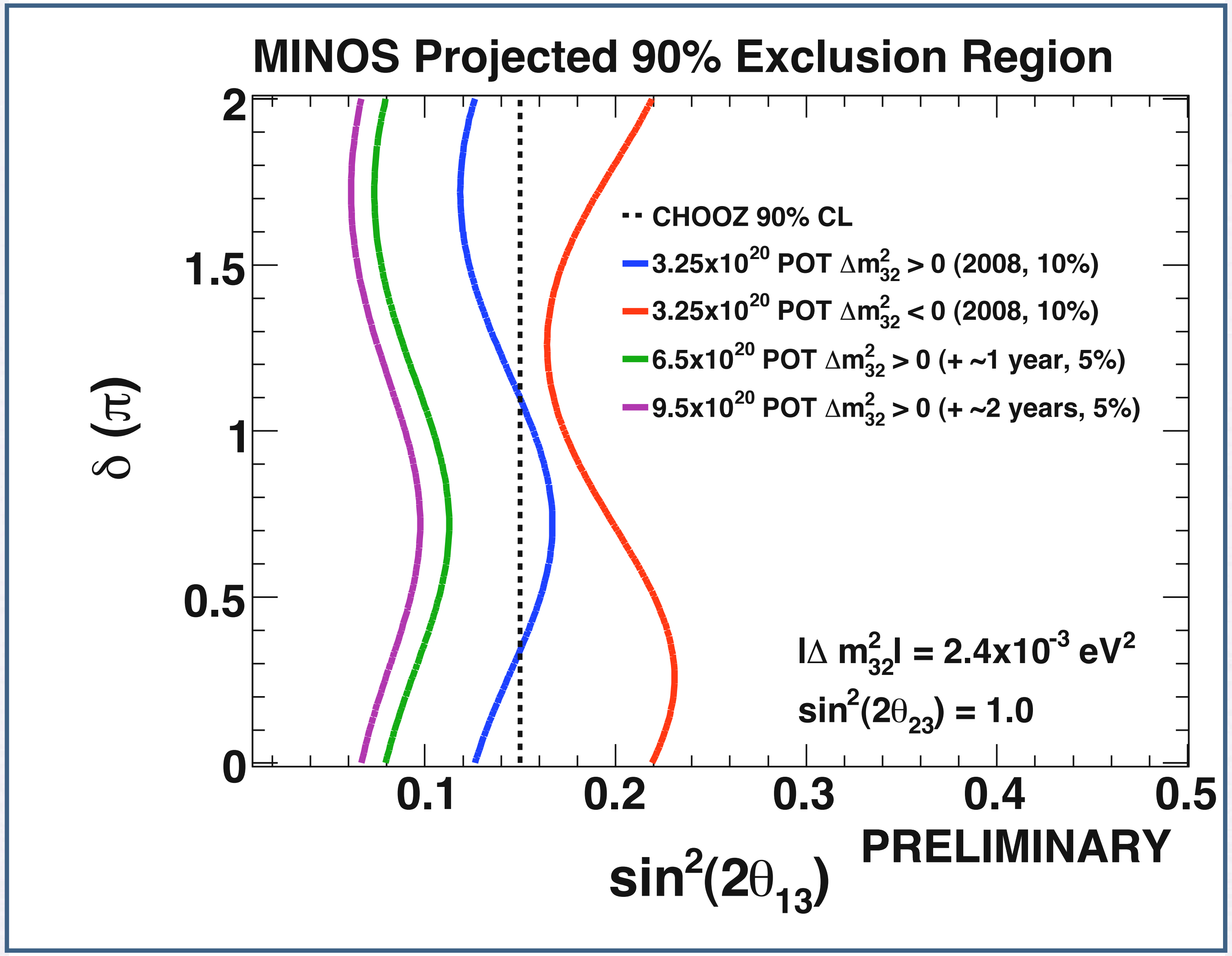
Results coming soon!

Sensitivity based on exposure for Run I+II. Reach comparable to the CHOOZ limit.

Physics reach of MINOS

Future data driven ν_e sensitivity

- Projected limits shown for expected MINOS exposures using normal hierarchy.
- Inverted hierarchy shown only for lowest exposure for simplicity.
- Data-driven systematics at 5% is a reasonable expectation as our understanding of the data improves.



It is possible with MINOS to achieve half the current CHOOZ limit!

Future plans and conclusions

- We have a robust physics program that will benefit from increased statistics through FY10; additional running in FY11 would probably be used to pursue additional physics goals.
- Once we are no longer competitive with other ν_e-experiments, we will consider alternate beam configurations such as running with anti-neutrinos.
- A configuration change could be requested sometime in FY10 depending on:
  - **Any hint of ν_e** , status of the competition, accelerator performance and Fermilab long range program including scheduling and other experiments.